Progress in heavy ion fusion research[a)]

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(Received 12 November 2002; accepted 20 January 2003)

The U.S. Heavy Ion Fusion program has recently commissioned several new experiments. In the High Current Experiment [P. A. Seidl *et al.*, Laser Part. Beams **20**, 435 (2003)], a single low-energy beam with driver-scale charge-per-unit-length and space-charge potential is being used to study the limits to transportable current posed by nonlinear fields and secondary atoms, ions, and electrons. The Neutralized Transport Experiment similarly employs a low-energy beam with driver-scale perveance to study final focus of high perveance beams and neutralization for transport in the target chamber. Other scaled experiments—the University of Maryland Electron Ring [P. G. O'Shea *et al.*, accepted for publication in Laser Part. Beams] and the Paul Trap Simulator Experiment [R. C. Davidson, H. Qin, and G. Shvets, Phys. Plasmas **7**, 1020 (2000)]—will provide fundamental physics results on processes with longer scale lengths. An experiment to test a new injector concept is also in the design stage. This paper will describe the goals and status of these experiments, as well as progress in theory and simulation. A proposed future proof-of-principle experiment, the Integrated Beam Experiment, will also be described. © *2003 American Institute of Physics.*
[DOI: 10.1063/1.1560611]

I. INTRODUCTION

The goal of the U.S. Heavy Ion Fusion (HIF) program is to produce commercial electricity by using multiple beams of heavy ions ($A \sim 100-200$ amu) at a few giga-electron volts to implode an inertial fusion target. In order to achieve this goal, space-charge-dominated beams must be accelerated and compressed to form ~ 10 ns pulses, then focused and propagated through the target chamber to the target. In present designs, the target chamber first wall is protected from radiation, neutrons, and debris from the fusion reaction by liquid jets of the molten salt FLiBe. As the beam propagates through the chamber, the charge state of the ions will be changed by several competing processes, including stripping and neutralization due to FLiBe vapor, and photoionization from target x rays. Much of the physics of beam propagation from source to target has already been explored in a series of experiments using low-energy beams with parameters scaled to produce the space-charge-dominated regimes of the fusion driver. Stable transport,[1] acceleration and compression,[2] beam combining,[3] and final focus[4] have been studied in this way. However these experiments were unable to study several important phenomena, among them electron effects such as neutralization (which requires a beam with driver-like current and beam perveance), and long spatial-length-scale phenomena (e.g., longitudinal wave physics, where the growth length of perturbations is longer than present experiments).

The present program is configured to address many of these issues. The High Current Experiment[5] (HCX) is using a beam of charge per unit length characteristic of the low-energy end of a driver in order to study transport limits. The Neutralized Tranport Experiment (NTX) is using a low-energy beam with a perveance characteristic of the high-energy end of a driver to study final focus and neutralization. Other scaled experiments are being used to study long-length-scale phenomena. The University of Maryland Electron Ring[6] (UMER) achieves long path length by recirculating particles in a ring, while the Paul Trap Simulator

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Experiment[7] (PTSX) confines particles for long times. Finally, a new concept has emerged for a ''multibeamlet'' heavy ion injector which, if successful, is expected to decrease injector size and cost. An experiment is being designed to test this concept. The status of all of these experiments will be described in Sec. II.

Due to the competing processes of neutralization and stripping noted earlier, beam propagation in the target chamber encompasses perhaps the most complicated physics of the heavy ion driver. Recent simulation results for bismuth ions (Bi^{+1}) show focusing adequate for the driver for both the initial low energy beams which begin the target compression, and for the main pulse beams. These simulations are described in Sec. III.

When present experiments have concluded, many heavy ion fusion driver issues will have been investigated in experiments tailored to study relevant physics for a given section of the driver. However, there remains a need to integrate the physics in a source-to-target experiment. Two experiments (the Scaled Final Focus Experiment[4] and the NTX), for instance, will have studied aspects of final focus physics, including aberration correction and neutralization at high perveance, but in both experiments the beam was focused directly after matching from the source, rather than, as in a driver, after transport with acceleration followed by longitudinal compression. Another experiment is required which would integrate the source-to-focus physics into a sequence, thus giving an approximation of the correct distribution function at the final focus system. This integrated proof-of-principle experiment, the Integrated Beam Experiment (IBX), is in the initial physics design stages now. Important physics which could not be studied in previous experiments is also included in its mission, namely, longitudinal drift compression, bending of space-charge-dominated beams, and some longitudinal beam physics experiments. The IBX will be described in Sec. IV.

II. THE PRESENT HEAVY ION FUSION EXPERIMENTAL PROGRAM

A. The High Current Experiment

The mission of the High Current Experiment is to explore the physics which limits the amount of beam that can be transported through an accelerator of a given aperture. This limitation on transport efficiency affects the eventual cost of a heavy ion fusion driver, and also determines the optimal aperture for future experiments. Particle-in-cell simulations predict that the ''dynamic aperture'' (i.e., the usable aperture as defined by beam dynamics) for the case of a perfectly aligned beam is determined only by the limitation of physical scraping of the beam at the aperture.[8] The High Current Experiment is testing this conclusion at beam intensities and pulse durations characteristic of those envisioned in HIF drivers near injection energy. It also will explore the effects of misaligned beams, beam–gas interactions, distributions with nonuniform density, and of beam envelopes mismatched to the focusing system, which are expected to produce beam halo.

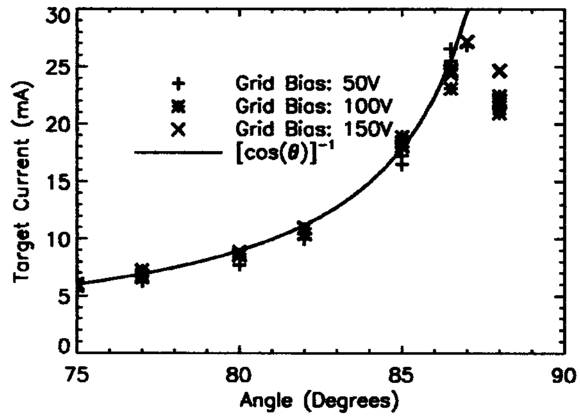

FIG. 1. Preliminary measurements of the electron emission coefficient, for 1 MeV K+ incident on stainless steel, follow the 1/cos(theta) dependence between 75° and 87° from normal incidence.

A 0.18 A, 4 μs, 1 MeV K^+ beam is presently being used for the dynamic aperture studies. Following a 6-quadrupole matching system, the beam is transported through a periodic alternating-gradient focusing system consisting of 10 electrostatic quadrupoles with 23 mm aperture. The beam has been aligned with the focusing channel to within 0.5 mm and 2 mrad, and its envelope matched to within 2 mm. When the beam is matched to fill 60% of the 23 mm radial aperture, no emittance growth (i.e., no beam heating) is observed during transport, in agreement with simulation. Subsequent experiments will increase the beam radius until degradation of beam quality occurs. Beam halo production will be measured, as well as desorption of gas from the walls as beam particles scrape the vacuum wall.

In contrast to electrostatic quadrupoles, in which the fields will sweep out electrons, in magnetic quadrupoles, which make up most of the transport system of the driver, electrons can persist and affect beam transport. Electrons produced by beam halo ions scraping the vacuum wall, or by ionization of background gas, will change the space charge of the beam, adversely affecting focusing, and perhaps even producing instability.

Experiments beginning now on the HCX will provide data to determine how large the beam pipe aperture must be in order that these effects be kept negligible. First the secondary electron and atom coefficient will be measured. Very little experimental data are available on the secondary electron and atom coefficients for the case of heavy ions at grazing incidence, the case most relevant to the driver, and of course the coefficient will vary with surface material and preparation. Preliminary HCX measurements of the electron coefficient are shown in Fig. 1. For these measurements the beam has been aimed at various angles to a metal plate. The data follow the cos(θ) dependence known from the literature,[9] and show a secondary electron coefficient which varies from 20 at 15° to 100 at 2° from grazing incidence. The distribution of electrons in the beam will be measured in an alternating gradient lattice of four pulsed quadrupole focusing magnets, which are instrumented to detect electrons and desorbed gas. These are ready to be installed at the end of the HCX transport lattice. Measurements will be made of

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the currents of electrons and ions produced by beam halo scraping the quadrupole surfaces and by background (and desorbed) gas ionization. Measurements of the ion distribution function, which gives the beam space-charge potential, can be used to calculate the radius at which the electron-ion pair was "born," and then the density of electrons versus radius can be calculated, with the help of particle simulation. Provision has been made to add induction cells in the gaps between quadrupole magnets to in order to study the effect of acceleration on electron accumulation and dynamics. Prototype superconducting quadrupoles have been built, and will also be installed in the HCX beamline to further the research into electron dynamics and gain operational experience with the focusing technology appropriate for most of a driver.

Extension of the HCX beamline by 20–30 electrostatic quadrupoles is also planned. This would allow more precise measurements of transport effects, which evolve over comparable lengths.

B. The neutralized transport experiment

The NTX consists of a 400 keV ion diode, followed by a 4-quadrupole magnetic final focus system, and 1 m of drift in which neutralization experiments will be performed. The beam is an 80 mA K^+ beam. Aperturing is done in order to vary the perveance and to improve beam quality by clipping off beam affected by diode aberrations. Particle-in-cell simulations using the LSP code[10] have shown that neutralization caused by passing the beam through a plasma can greatly improve the beam focus.[11] In a driver this can be done by inserting a "plasma plug," with a density ($\sim 10^{13}$ m^{-3}) which is significantly higher than the beam density, into the beamlines after the final focus system. Two other sources of electrons are available to neutralize the beam: electrons produced by beam ionization of FLiBe vapor in the chamber, and, after ignition, electrons in plasma formed around the target by photoionization of FLiBe vapor by x rays from the hot target. Both of these mechanisms will be simulated in the NTX. A pulsed metal plasma arc source of length 10 cm and $>10^{10}$ cm^{-3} density is located 20 cm from the last focusing lens, to simulate the plasma plug. A 10-cm-long electron cyclotron resonance plasma source providing a 10^{12} cm^{-3} argon or helium plasma will be installed soon farther downstream. The spatial density profile from this source can be tailored by varying the axial profile of a solenoidal field around the beam pipe, in order to simulate the spatial distribution expected for the photoionized plasma.

Construction of the NTX has just been completed, and machine commissioning is in progress. Early data from the NTX showing a large improvement in focusing when the plasma plug is present are shown in Fig. 2.

Optimization of the focus of the 4-quadrupole final focus lens system, including minimization of higher-order aberrations, will also be studied in the coming months on the NTX. In the future, octupole windings may be inserted in the bore of the focusing system magnets for studies of the correction of third-order aberrations. Though aberration correction is well-understood in other optical systems, techniques are largely untested for high perveance beams.

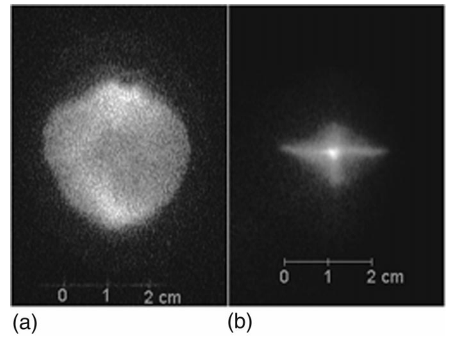

FIG. 2. Beam profile (300 kV 25 mA potassium ions) at the end of the plasma drift section for (a) plasma source turned off, and (b) plasma source on.

C. Small, scaled experiments

Two small experiments are beginning fundamental studies in intense beam physics important to heavy ion fusion. One is the University of Maryland Electron Ring, and the other is the Paul Trap Simulator Experiment at Princeton Plasma Physics Laboratory. In both of these experiments long-length-scale phenomena can be studied, because the particles are confined over many betatron periods. In UMER this is done by circulating the beam in a small fast-cycling synchrotron. The PTSX confines ions in a Paul trap for long times (~ 45 s), and time-dependence of the voltage on the radial-confinement electrodes simulates the passage of focusing quadrupoles in the "beam frame." Both experiments are in the beginning stages of operation. They are described in the following.

1. The University of Maryland Electron Ring

UMER uses a nonrelativistic electron beam to simulate intense ion beam physics in a compact (11.52 m circumference) experiment. The accelerator is designed to have access to a wide range of beam parameters. The phase advance per focusing period of the transverse oscillation of a particle in the focusing field, σ, is the "depressed betatron phase advance." The ratio of this number to the value of the phase advance neglecting space charge, the "undepressed betatron phase advance," σ_0, is a measure of the influence of space charge on the beam. In UMER, σ/σ_0, can vary from 0.8 to 0.2, a range which takes beam dynamics from emittance-dominated to space-charge-dominated. The input beam current is variable from 0.4 to 100 mA, giving a generalized perveance of 0.0006–0.0015. At 10 keV, the normalized emittance for 100 mA is 15 mm mrad. The pulse length can be varied from 40 to 100 ns. These parameters overlap the heavy ion fusion regime. At present, 18 focusing quadrupoles out of 72 have been installed in the ring. The ring is expected to be completed in the summer of 2003. The 100 mA beam shape in the injector, as measured by a phosphorescent screen, is shown in Fig. 3.

When the ring is completed, multi-turn operation will be attempted, the goal being to attain 100 turns at low current (10 mA) and 10 turns at high current (100 mA), with final emittance within a factor of 4 of the initial value. Subsequent upgrade of UMER would allow for ramping the dipoles, to enable acceleration of up to 2 keV per turn.

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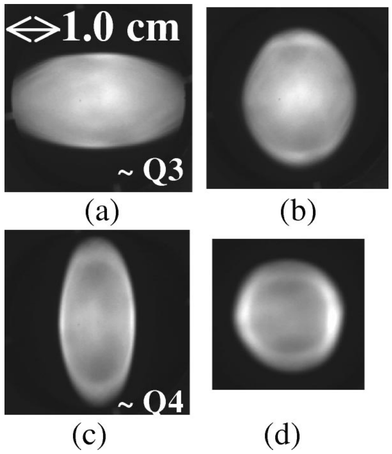

FIG. 3. Photos of integrated beam cross-section in several planes of the injector, obtained using a phosphor screen and a CCD camera, for the 100 mA intense beam; locations of screen: (a) 71 cm, (b) 85 cm, (c) 91 cm, and (d) 103 cm, all measured from the anode plane.

2. The Paul Trap Simulator Experiment

In the Paul Trap Simulator Experiment, cesium ions with density 10^6 cm^{-3} are injected into a gold-plated metal cylindrical vacuum chamber. The conducting walls are split into four electrodes (see Fig. 4) which are charged as shown in the figure. At the ''beam,'' whose radius ($r_p \sim 1$ cm) is much less than the 10 cm wall radius, r_w, the field is that of a quadrupole, with small corrections of order $(r_p/r_w)^4$. The wall voltage, V_0, oscillates at 100 kHz, simulating passing quadrupoles of a transport system as seen in the beam frame. Waveforms can be varied to explore the effects of different variations of quadrupole field with z. Positive voltage on the cylinder endplates provides longitudinal confinement. The end-to-end bounce time in the 2-m-long experiment is a factor of 30–40 (depending on parameters) larger than the betatron period (i.e., the period of the transverse oscillation of the particles due to the transverse focusing), minimizing the effect of the ends on dynamics. The long (~ 45 s) confinement time makes possible the study of slow-growth-time phenomena. The experiment will be used to study beam mismatch, envelope instabilities, halo production, beam compression techniques, longitudinal wave physics and beam profile effects.

Experiments on the PTSX began in June 2002. Figure 5 is early data showing the current produced by the source as a function of V_0 and wall voltage frequency. Longitudinal confinement is not provided for this experiment—the ions are free-streaming longitudinally. The calculated area of known envelope instability is to the left of the white parabola in Fig. 5, and its effect on ion density can be seen in the contours of current measured by a Faraday cup at the end of the experiment. The change in ion profile as the instability is approached is also shown in the figure.

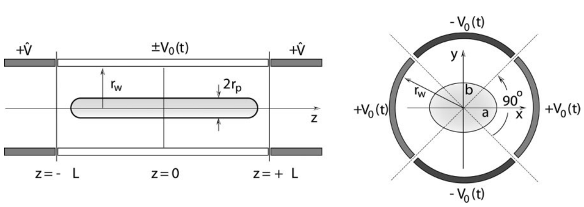

FIG. 4. PTSX consists of three 8-in.-diam cylinders, each divided into four 90° sectors. An ac voltage on the central cylinder confines the ions radially while a dc voltage on the end cylinders confines the ions axially. By varying the functional form of $V_0(t)$, the effects of various quadrupole magnet configurations can be explored. Side (left) and end views are shown.

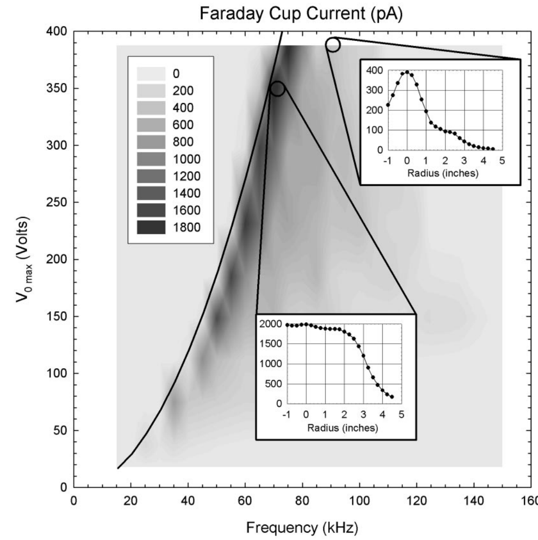

FIG. 5. Steady state currents for ions traveling directly from the ion source to the Faraday cup. If the vacuum phase advance (σ_0) is greater than 90° (area to the left of the white parabola), the particle orbits are unstable and all ions strike the trap wall before reaching the Faraday cup.

D. Multibeamlet injector test experiments

As the voltage on a diode is increased, in order to increase the current generated, its length must increase in order to avoid electrical breakdown. The Child–Langmuir equation, combined with voltage breakdown scaling, shows that if the ratio of the length of a diode to its diameter is held constant in order to maintain good optics, the current density must decrease as voltage and total current increase. Thus beams of smaller diameter produced by a diode have higher current density than large-diameter beams. This offers the opportunity of making a more compact diode and injector (the accelerator section directly after the diode) if each accelerator beam can be made by merging small-diameter bright beamlets. Another advantage of this merging mini-beamlet approach is the possibility of greatly reducing the size of the ''matching section.'' In the conventional accelerator design, a matching section with diameter larger than that of the injector is needed to transform the round-cross-section of beams emitted from the diode to the elliptical cross-section required for the alternating gradient focusing system of the accelerator. The diameter of this section can be substantially reduced with the ''multibeamlet'' approach, since the merging beamlets can be arranged in an elliptical pattern of the correct size for the accelerator. A potential problem is the emittance growth inherent in the merging process. Two- and three-dimensional particle-in-cell simulations of the merging process,[12] using the WARP code,[13] produce a final transverse emittance of 0.8–1.4 π mm mrad. While this

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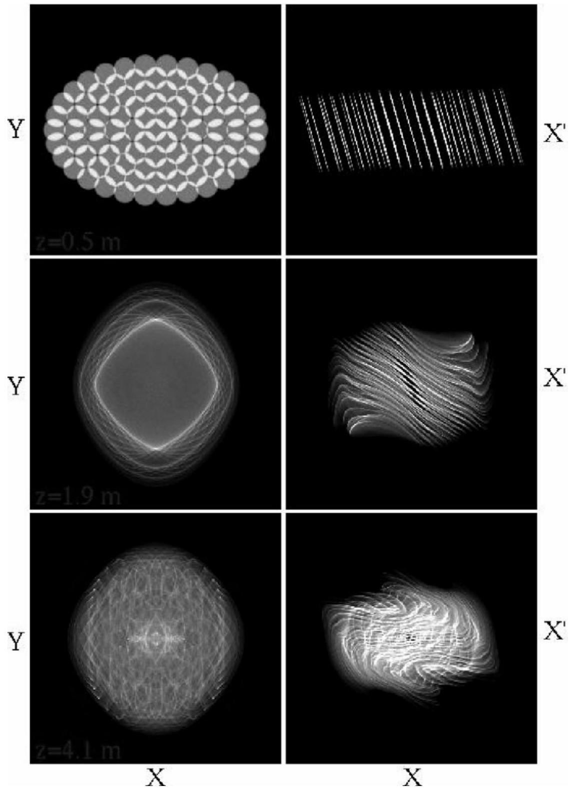

FIG. 6. PIC simulation of 91 beamlets (0.5 A total) in a multibeamlet injector. Number density in configuration and phase space is shown beginning where the beamlets begin the merge. Final normalized emittance is just under 1 π mm mrad.

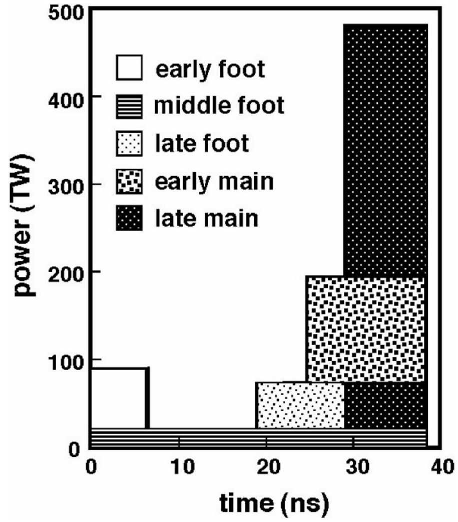

FIG. 7. Input-power profile delivered to the target by 120 constant-current beams with different durations and timings.

emittance is approximately double that from a conventional single emitter diode, it is within acceptable limits for current driver designs. The final emittance shows a very weak dependence on the source temperature, allowing considerable flexibility in the ion source choice. Figure 6 shows the evolution of the beam density and phase space. Within 40 m, it approaches uniform density, with acceptable uniformity in phase space.

An experimental test of this concept is in the design stage. In the first stage, in FY03, approximately one-hundred 5 mA, 80 keV Ar^+ beamlets will be produced by placing a multi-aperture extraction diode in front of a plasma ion source. The beamlets will propagate in parallel. Plates perpendicular to the direction of travel, with apertures for each beamlet, will be biased in order to provide Einzel lens focusing. Beamlet alignment, electron and gas production, and beam quality will be measured. In the second stage, an experiment on the LLNL 500 kV test stand will accelerate the beamlets to 500 keV and merge them. Emittance growth due to merging, alignment, and phase and spatial profiles of the final merged beam will be measured. If successful, this concept could lead to a lower-cost, smaller-diameter, lower-weight multibeam injector.

III. NEUTRALIZATION AND CHAMBER PROPAGATION SIMULATION RESULTS

An extensive theory and simulation effort supports the above-described experiments, and explores driver issues. Because of space limitations, only one important highlight of this effort is described here. For overviews of HIF theory please see the following recent reviews: R. C. Davidson *et al.*, Laser Part. Beams **20**, 377 (2003); and D. R. Welch, D. V. Rose, B. V. Oliver, T. C. Genoni, R. E. Clark, C. L. Olson, and S. S. Yu, Phys. Plasmas **9**, 2344 (2002).

The LSP code, a three-dimensional multi-species electromagnetic particle-in-cell code, has been used for axisymmetric simulations of heavy ion beam propagation through the target chamber. Many complicated effects were included in the simulations: neutralization by plasma injected into the beampipe just upstream of the chamber entrance, by electrons emitted by the conducting wall near the entrance, and by those from collisional ionization by the beam of FLiBe vapor; beam stripping by FLiBe vapor and by x rays from the target; and beam neutralization and stripping by the plasma formed by photoionization of vapor around the target. Beam parameters were chosen to match a recent version of the distributed-radiator indirect-drive target introduced by Tabak and Callahan,[14] which requires 6.5–7 MJ total input energy. The energy must be deposited within annuli of half-width 2.2 mm at each end of the target. This means that 90%–95% of the energy of each beam must focus in a circle of radius 2.2 mm. The correct energy-deposition time profile for target compression is produced by phasing the arrival of beams of different energy, as sketched in Fig. 7. Focusing is most difficult for the earliest beams to arrive (the so-called ''foot pulse'' beams), and for the shorter of the main pulse beams. The earliest foot beams arrive before the target is heated sufficiently to photoionize the nearby FliBe vapor, so these pulses must reach the target without neutralization by photoionization electrons that are available to later pulses, while the shorter main pulse beams have the highest current and perveance, and therefore the largest space charge forces before neutralization. Parameters for these two types of beam were used in the simulations described in the following.

LSP calculations[11] were done with a 7×10^{12} cm^{-3} density of BeF_2 in the chamber. This density is appropriate for

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the thick liquid wall (i.e., FLiBe jet) chamber. BeF_2 is the dominant gas component of FLiBe vapor and has been shown by simulations to adequately represent the vapor. For the 9.3 ns, 2 kA, 4 GeV main pulse Bi^+ ions, less than 1% fell within the required 2.2 mm radius spot when no plug plasma or photoionized plasma was present. Adding a layer of plasma 10 cm thick (with 3 cm parabolic density falloff at the ends of each plasma) at each end of the 3-m-long beam port, increased this percentage to 92% when the ionization length of the plasma was of the order of the distance to the target. This value rose to 94% when the effects of neutralization by the photoionized plasma were included. Beam focusing was insensitive to the length and density of the injected plasma layers so long as enough plasma electrons were available to neutralize the beam. However the scale length for the density falloff at the upstream end of the first layer was found to affect the transverse emittance, and therefore the focal spot, of the beam. More gradual profiles decreased the rms spot radius by decreasing the electron current directed into the beam from the head as the beam reached the plasma.

Foot pulse focusing was also greatly improved by the addition of the preneutralizing plasma plugs. For a 1.5 kA, 3 GeV bismuth beam, 85% of the foot pulse focused within the required 2.2 mm radius. This value increased to 92% when the plasma density scale length was doubled. Thus focusing adequate for the driver was achieved for both foot and main pulse beams.

Changing the ion from bismuth ($A=209$ amu) to xenon (131 amu) decreased the percent of ions focused within 2.2 mm to 60% for the foot pulse, and 81% for the 9.3 ns main pulse. Using xenon is desirable because the lighter mass decreases the cost of the accelerator. Though adequate focusing has not yet been demonstrated for xenon, the system is not optimized, and it is likely that the spot size can be reduced.

IV. PLANS FOR AN INTEGRATED BEAM EXPERIMENT

When the present experiments are completed, the HIF program will have experimentally demonstrated production and stable transport of intense beams, beam compression, limited acceleration and compression of multiple beams, beam combining, final focus with aberration correction, and beam neutralization. Many beam dynamics effects, including halo production and electron production and dynamics, will have been studied. The physics which will remain for future experiments includes bending of space-charge-dominated beams, the final drift compression, multiple beam physics (including interaction of the high-current beam bundle with the induction core impedance), very-long-length-scale physics such as longitudinal wave growth (which will be studied on the small-scale experiments, but must be repeated in the induction linac system) and high current/high energy physics, such as neutralization with non-negligible beam self-magnetic field. But along with exploration of these areas, it is also important to integrate the physics previously explored into a sequential experiment. While it was crucial to isolate the physics of each driver section in controlled, affordable experiments, the beam manipulations involved must now be integrated into a sequential system so that the evolution of the distribution function through all of the sections can be followed. In this way the physics of the individual sections can be studied with a distribution function which has been modified by previous sections, as in a driver.

The HIF program has begun to plan a proof-of-principle experiment, the Integrated Beam Experiment (IBX), which would investigate many of the remaining physics issues mentioned earlier, and which would also be an integrated test of source-to-focus beam physics. The IBX accelerator is at present envisioned to be a single beam K^+ accelerator with final ion energy $\sim 5-10$ MeV and driver-scale perveance, variable between 10^{-5} and 10^{-3}. To reduce cost, though the beam would be driver-scale in transverse dimension and charge-per-unit-length, the pulse length would be reduced to $\sim 0.2-1.5\ \mu$s full width at half maximum at injection. This can be compared to the driver pulse length at this energy, which is a few tens of microseconds.

Flexibility is being designed into the accelerator so that a range of acceleration and compression schedules can be examined. Experiments on longitudinal wave propagation and growth, beam compression during acceleration, drift compression (up to the factor of ~ 20 needed in the driver), beam bending, and the effect of electrons on ion transport will be possible, along with studies of integrated drift compression/final focus/neutralization/chamber transport. The IBX would be a large step forward. However, the separate pieces of physics, of beam acceleration, focusing, and compression, needed for the IBX will have been demonstrated in small-scale experiments, and the technology, including superconducting magnets, will be prototyped in the HCX and in offline experiments. Present experiments, especially the HCX, NTX, and multibeamlet injector, will provide information which will optimize the design of the IBX and all subsequent experiments. The dynamic aperture experiments on the HCX, for instance, will optimize the aperture diameter, and the NTX data will be used to optimize the magnet design for the final focus. But the design of the IBX can be done without this information, and later adjusted to the optimized values. Costing studies indicate that for a single-beam accelerator the effect of these changes on total cost would be minimal (e.g., $\sim 5\%$ change in total cost for a 1 cm change in the 4 cm aperture). Construction of the IBX could begin in 2005, if funding were available.

The IBX will not be able to investigate multiple beam and high current/high energy beam dynamics or very-long-length-scale dynamics. Exploration of these issues would be the mission of the Integrated Research Experiment (IRE)—a several-hundred mega-electron volt, multibeam, source-to-target experiment. The IRE would also be able to perform a limited set of experiments on heavy-ion-related target hydrodynamics, though most target issues would be tested on the National Ignition Facility.

V. CONCLUSIONS

In summary, four new experiments are beginning to produce data for the Heavy Ion Fusion program. They include

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experiments on transport limits (High Current Experiment), and final focus and neutralization (Neutralized Transport Experiment), and small-scale experiments on long-length-scale issues and fundamental beam dynamics (the University of Maryland Electron Ring and the Paul Trap Simulator Experiment). A fifth experiment, which will investigate the feasibility of a new ''multibeamlet injector'' concept, will be in operation in mid-2003.

Along with these experiments, a program of simulation and theory serves to both support experimental data analysis and design, and explore driver issues which are not in reach of present experiments. Recent simulations have demonstrated focusing of both foot and main pulse beams onto the 2.2 and 1.8 mm spot required by present targets. Effects of ionization of the beam and ambient vapor by target x rays, neutralization by electrons emitted from the wall and from plasmas in the beam pipe, and stripping by x rays and background gas were included in the calculation. Preneutralization by plasmas in the beam port was especially important in the focusing process.

The present experiments will conclude a sequence of experiments that will have demonstrated most of the physics of the heavy ion driver. A proof-of-principle experiment, the Integrated Beam Experiment, is planned to succeed this phase. The IBX will demonstrate integrated source-to-focus transport, acceleration, compression, and focusing of a single beam, and will explore many of the remaining physics issues of heavy ion drivers, such as longitudinal dynamics, beam bending, and integrated drift compression/final focus/chamber transport.

ACKNOWLEDGMENTS

This work was supported by the Office of Science, U.S. Department of Energy, under Contract Nos. DE-AC03-76SF00098, W-7405-Eng-48, DE-AI02-93ER40799, DEFG02-94ER40855 and DEFG02-92ER54178, and DE-AI02-94ER-54232.

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